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evaporation rate during the test and total evaporative weight loss were obtained with a Potter platform balance. Skin wettedness was calculated from the measured dew points and temperatures. The differences in knit structure of the underwear in the clothing systems resulted in significant differences in mean skin temperature, local and average skin wettedness, non-evaporated and evaporated sweat during the course of the intermittent exercise test. No differences were observed in the course of the core temperature.

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THERMOREGULATORY RESPONSES TO INTERMITTENT EXERCISE ARE INFLUENCED BY KNIT STRUCTURE OF UNDERWEAR

Ruth Nielsen[1] and Thomas L.Endrusick[2].

1) Climate Physiology Division
National Institute of Occupational Health
S-17184 Solna, Sweden.

2) Military Ergonomics Division
U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007, USA.

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Address correspondence to:
Dr. Ruth Nielsen,
IFK/National Institute of Occupational Health,
Ekalundsvägen 16,
S-17184 Solna,
Sweden.
Telephone: +46-8-7309100
Telefax : +46-8-7301967

SUMMARY:

The purpose of this study was to evaluate the role of knit structure in underwear on thermoregulatory responses. Underwear manufactured from 100% polypropylene fibers in five different knit structures (1-by-1 rib, fleece, fishnet, interlock, double-layer rib) were evaluated. All five underwear prototypes were tested as part of a prototype clothing system. Measured on a thermal manikin these clothing systems had total thermal resistances, I_{tot}, of 0.243, 0.268, 0.256, 0.248 and 0.250 $m^2 \cdot K \cdot W^{-1}$, respectively (includes I_a=0.104 $m^2 \cdot K \cdot W^{-1}$). Human testing was done on eight male subjects and took place at T_a=5°C, T_{dp}=-3.5°C and V_a=0.32 $m \cdot s^{-1}$. The test comprised a repeated bout of 40 min cycle exercise (315 $W \cdot m^{-2}$; 52±4.9% $\dot{V}O_2max$) followed by 20 min of rest (62 $W \cdot m^{-2}$). $\dot{V}O_2$, heart rate, esophageal temperature, local skin temperatures, ambient air temperature, dew point temperature at three skin sites and in the ambient air were monitored. Onset of sweating was evaluated from the dew point sensor recordings. Non-evaporated sweat accumulated in the clothing was determined. Changes in the subject's evaporation rate during the test and total evaporative weight loss were obtained with a Potter platform balance. Skin wettedness was calculated from the measured dew points and temperatures. The differences in knit structure of the underwear in the clothing systems resulted in significant differences in mean skin temperature, local and average skin wettedness, non-evaporated and evaporated sweat during the course of the intermittent exercise test. No differences were observed in the course of the core temperature.

Keyword: thermoregulatory responses, cold, intermittent exercise, underwear

INTRODUCTION

Thermoregulatory responses of the nude man resting and exercising in various thermal environments are well described (Saltin and Hermansen 1966; Stolwijk et al. 1967; Nielsen 1969). This is not the case for the dressed man. The clothing intervenes as a dynamic thermal enclosure around the human body creating a thermal microenvironment. Clothing buffers the heat exchange of man with the surrounding climate; however, it may also limit the possibilities for heat dissipation. The addition of clothing produces different thermoregulatory responses at the skin of the dressed man compared to the nude man. Mean skin temperature, skin temperature distribution, evaporation of sweat and skin wettedness are some of the responses that may change with different clothing parameters. The heat exchange between the skin surface under the clothing and the ambient environment through the clothing worn on moving man cannot be explained only in terms of standard textile characteristics. In addition to the heat exchange across the textile layers, passive and forced convective air movements in the clothing and through the openings of the garment remove a varying amount of heat energy depending on garment design, and also on body movements, air velocity, wetting, compression and other factors (Hall and Poltke, 1956; Nielsen et al., 1985). Also, changes in ambient air humidity or sweating will change the humidity within the clothing which may produce wetting of the clothing. As a result, transient heat exchange starts to develop within the clothing. This affects the heat exchange between the skin surface and the microenvironment, and provides a feedback to the thermoregulatory responses at the skin surface.

Common clothing ensembles used in cold environments are comprised of two or more clothing layers: underwear, possibly middle layers, and an outer clothing layer. The majority of the skin surface is not in contact with the ambient environment, but with the micro environment under the clothing and the underwear itself. Thus, underwear has a special function in relation to the sensation of the fabric-to-skin interface and may also be of importance for the resulting micro-environment over the skin.

In the literature (Fonseca 1970) the addition of thermal underwear to a clothing system is supposed to add little extra warmth and protection for the wearer, and in terms of differences in intrinsic

thermal resistance of the underwear measured on a thermal manikin these differences are insignificant as long as the fit and design remain the same (Olesen and Nielsen 1983). However, it was shown on humans that the textile material in the underwear of a clothing system slightly influences the thermoregulatory responses during intermittent exercise in a cold environment (Holmér 1985).

The purpose of the present study was to investigate if underwear manufactured from the same fiber type material, but in different knit structures, as a part of a clothing ensemble, caused different thermoregulatory responses in persons performing intermittent exercise in an environment resulting in both periods of sweating and chilling.

MATERIAL AND METHODS

Garment description. Underwear manufactured from 100% polypropylene fibers in 5 different knit structures (1-by-1 rib (K1), fleece (K2), fishnet (K3), interlock (K4), double-layer rib (K5)) were evaluated. Measurements of selected physical characteristics of the experimental textiles were performed on single and multi-layer samples of cloth in accordance with standard procedures: fabric thickness in mm (ASTM: D1774-64), thermal resistance in $m^2 \cdot K \cdot W^{-1}$ (ASTM: D1518-77) and water vapor resistance in $m^2 \cdot Pa \cdot W^{-1}$ (DIN: 54101). The results are shown in Table 1. Before any testing was done, all samples were laundered and air-dried five times without the use of any detergent. This was done to remove excess finishing chemicals in the textiles. All five underwear prototypes were tested as part of a typical, standardized clothing system on human subjects. The clothing system was comprised of a two-piece long-sleeved /long-legged underwear ensemble, a Battle Dress Uniform (BDU) shirt and trousers (50% cotton/50% nylon), woolen socks, gym shoes, and woolen gloves. Each subject had his own separate clothing system. Before any testing was done on humans, all underwear and the rest of the clothing system were laundered as described above. For each subject, the order in which the experimental underwear was tested, was randomized. Insulation values of all five clothing systems and all five underwear ensembles were measured on a thermal manikin (Madsen 1971) (Table 1).

Subjects. Eight healthy males volunteered for the present series of experiments. Before any testing, the subjects were informed about the purpose of the study, any known risks and their right to terminate participation without penalty. They expressed understanding by signing

a statement of informed consent. None of the subjects did more than two test sessions per week. They had an average (±s.d.) age of 23±4.9 years, weight of 74±11.6 kg, height of 177±4.7 cm, DuBois surface area (A_{Du}) of 1.91±0.146 m^2, maximal oxygen consumption of 3.34±0.644 liters $O_2 \cdot min^{-1}$, and percentage body fat of 16±5.2 %.

Determination of body density was obtained from hydrostatic weighing (Goldman and Buskirk 1961), and percent body fat was estimated from density (Siri 1956). A_{Du} was determined by use of the DuBois equation (DuBois and DuBois 1916). Maximal aerobic power ($\dot{V}O_2max$) was determined for each subject during seperate tests using a continuous progressive work-load protocol on a cycle ergometer (Rowell 1974).

Experimental protocol. Conditions were designed so as to mimic real-life situations in which sweating and after-exercise chill would develop, and where this type of clothing would normally be worn. Testing occurred in a climatic chamber at an air temperature (T_a=T_g) of 5.0±0.52°C, a dew point temperature of -3.5±0.31°C (~54 % relative humidity), and an air velocity of 0.32 $m \cdot s^{-1}$. The air flow was created by large fans and directed towards the front of the subject.

To standardize the initial heat content of the five clothing systems and thus eliminate this as a factor of variation for the heat exchange body-clothing-environment during the experiment, a rigid procedure was followed. The clothing was stored in the antechamber at an air temperature of 29°C and 20% relative humidity (6.0 kPa) at least two hours before the experimental procedure began. The elaborate, standardized dressing procedure of the subject also took place in this antechamber. Each subject reported to the laboratory at the same time of the day for all experiments to avoid any circadian variation in body temperature. After arrival he was weighed in the nude and then instrumented with chest electrodes for heart rate (HR), thermocouples for esophageal and skin temperatures. Each piece of clothing, including the shoes, was weighed and then put on the subject. When he was completely instrumented, a dressed weight was recorded. Upon entering the test environment the subject was instrumented with dew point sensors on the skin underneath the garment before he mounted a cycle ergonometer placed on a Potter balance. Zero was adjusted on the balance and a calibration was done at this time. Approximately ten minutes after entering the test chamber the subject began the 2-hour test. The test comprised a twice repeated bout of 40 minutes cycle

exercise (60 r.p.m.; 1.8±0.37 kp) followed by 20 minutes of rest on the ergonometer (EX1, RE1, EX2 and RE2). Each subject always exercised at the same exercise intensity, that had been chosen so it would approximate 55% of his $\dot{V}O_2$max. Esophageal, skin and air temperatures, as well as dew point temperatures at the skin and in the ambient air were monitored on a HP200 computer every minute during the test and stored for analysis. Changes in body weight were sampled every 20 seconds on a HP85 computer and HR was recorded every 10 minutes. $\dot{V}O_2$ and $\dot{V}CO_2$ were measured during the last 5 minutes of the first exercise and rest period, respectively. Two minutes after cessation of the test the subject left the test chamber and undressed immediately in the antechamber. Nude body weight and individual clothing component weights were recorded after the subject had undressed.

<u>Physiological variables</u>. Electrocardiograms were obtained with chest electrodes and a electrocardiograph (HP1500B). Oxygen uptake ($\dot{V}O_2$, liters $O_2 \cdot min^{-1}$, STPD), Carbon Dioxide excretion and pulmonary ventilation were measured by open circuit spirometry using an automated system (Sensormedics Horizon MMC). Internal temperature (T_{es}) was measured by a thermocouple-tipped catheter inserted through the nose into the esophagus to the same level as the heart. Skin temperatures were monitored with a nine-point thermocouple skin harness (calf, thigh, chest, lower back, upper back, upper arm, forearm, hand, and forehead). The thermocouples were constructed in such a way that they could make skin contact without being covered by tape.

Dew point temperatures at back, chest and thigh were obtained by use of automatic dew point sensors (Graichen et al. 1982) directly attached on the skin underneath the garment. Onset of sweating was evaluated from the dew point sensor recordings. Sweat accumulation in the clothing was determined by repeated weighing of each individual clothing component, including the shoes, on a Sauter balance (model K12). Changes in the dressed subjects evaporation rate during the test were obtained with a Potter platform balance (model 23B). Total evaporative weight loss from the subject was determined from the Potter balance recordings, and in addition by weighing the dressed subject on a Sauter balance (model KR120) before and after the experiment.

CALCULATIONS

Metabolic energy production (M) was calculated from the measurements of

oxygen consumption ($\dot{V}O_2$) as (Gagge & Nishi 1977)

$$M = (0.23RQ+0.77)\cdot\dot{V}O_2\cdot k\cdot 60\cdot A_{Du}^{-1} \qquad (W\cdot m^{-2})$$

in which RQ is the respiratory exchange ratio, $\dot{V}O_2$ is the oxygen consumption in liters $O_2\cdot min^{-1}$, and k is the energy equivalent of oxygen (5.873 $W\cdot h\cdot$liters $O_2\cdot min^{-1}$).

Mean skin temperature ($\bar{T}_{sk}$) was calculated as an area-weighted average of measurements from the nine different skin sites using the formula (modified from Gagge and Nishi 1977):

$$\bar{T}_{sk} = 0.05T_{hand}+0.07(T_{forearm}+T_{upperarm}+T_{head})+0.20T_{calf}+0.19T_{thigh} +0.175(T_{chest}+(T_{upperback}+T_{lowback})/2) \quad (^\circ C)$$

Body temperature, T_{body}, was calculated as (Hardy and DuBois 1938)

$$T_{body} = 0.8T_{es} + 0.2T_{sk} \qquad (^\circ C)$$

Evaporative heat loss from the dressed subject (Sw_e) during the experimental period was determined from the continuous monitoring of weight loss on the Potter balance corrected for weight of respiratory water loss ($E_{res}\cdot(0.68\cdot 60\cdot A_{Du})^{-1}$ $g\cdot min^{-1}$) (Fanger, 1970) and metabolic weight loss ($\dot{V}O_2\cdot(44\cdot RQ-32)/22.4$ $g\cdot min^{-1}$). This weight loss rate converts to the evaporative heat loss rate (E_{sk}) in $W\cdot m^{-2}$ by multiplying by the factor $0.68\cdot 60\cdot A_{Du}$, where 0.68 is the latent heat of water ($W\cdot h\cdot g^{-1}$). Dripping rarely took place, because excessive sweat was absorbed in the clothing. Total non-evaporated sweat loss (Sw_{ne}) was measured as the difference between clothing weight before and after the experiment corrected for weight of water absorbed in the clothing from the environment. Hanging the preconditioned clothing system in the experimental environment for 130 minutes resulted in a weight gain of 18g. Total sweat loss over the test period (Sw_{tot}) was calculated as the sum of Sw_e and Sw_{ne}.

Vapor pressures at the skin surface and in the ambient air were determined from the local dew point temperature recordings using the Antoine equation. Assuming that the measured vapor pressure at the skin surface (P_{sk}) obtained from the dew point sensor truly reflected E_{req}. local skin wettedness (w) on back, chest and thigh was calculated as $w=(P_{sk}-P_a)/(P_{ssk}-P_a)$, where P_{ssk} is the saturated vapor pressure at the local skin temperature and P_a is ambient water vapor pressure. An average skin wettedness for thigh and torso area was estimated using the actual local skin surface area's fraction of the total body surface area:

$$w = (0.175w_{chest} + 0.175w_{back} + 0.190w_{leg})/0.54$$

Statistical analysis: Repeated-measures analysis of variance (ANOVA) was used to determine whether the factor 'knit structure' had any significant effect on thermoregulatory responses during the course of the test or on sweat accumulation in the clothing. An ANOVA was calculated on the data of esophageal temperature, local and mean skin temperatures, local and average wettedness and skin evaporation for every 10 minute (averaged over 8, 9 and 10 minute, and so on). In the event that ANOVA revealed significant main effect, Tukey's critical difference was calculated and used to locate significant difference between means. A paired t-test was used to test if there was any difference in thermoregulatory responses between the first and second test period. Data are presented as means±s.d. All differences reported are significant at the $p<0.05$ level.

RESULTS

Physiological observations. The factor subject had a significant influence on all physiological variables.

Work intensity (W) averaged 56±9.01 $W \cdot m^{-2}$ during the 40 minutes bicycle periods, and 0 W during the 20 minutes rest periods

The metabolic energy production (M) measured during exercise averaged 315±45.5 $W \cdot m^{-2}$ and during rest 62±11.9 $W \cdot m^{-2}$. M was not influenced by the clothing system worn. The exercise intensity corresponds to 52±4.9% of the subjects' $\dot{V}O_2$max.

Core temperature as represented by T_{es} (Figure 1) was not influenced by the knit structure of the underwear worn, except at 50min where T_{es}(K5) was higher than T_{es}(K1). In the first minute of EX1 T_{es} averaged 36.7± 0.24°C for all 40 tests. After 10 to 20 minutes of exercise a steady-state value of 37.5±0.20°C was reached. During RE1 T_{es} decreased quickly to reach an average value of 36.9±0.17°C just before the start of EX2. The course of T_{es} during EX2 and RE2 was similar to its course during EX1 and RE1, and similar temperature values were measured at the end of the two periods.

Mean skin temperatures. Average values for mean skin temperature and local skin temperatures for each clothing system are plotted in Figure 1. Except for the very first minutes of the test, the knit structure of the underwear always significantly influenced $\bar{T}_{sk}$. At the beginning of EX1 $\bar{T}_{sk}$ averaged 31.3±0.75°C (n=40). During the first 10 to 20 minutes all mean skin temperatures decreased, although this took place at

different rates dependent on the knit structure of the underwear worn. After 10 minutes of EX1, $\bar{T}_{sk}$(K3) was significantly lower than $\bar{T}_{sk}$(K2) and this difference persisted throughout the rest of the 2-hour test. While $\bar{T}_{sk}$(K3) during EX1 continued to decrease to reach a steady state value of 30.1±0.76°C, $\bar{T}_{sk}$(K2) began to increase after 17 minutes of exercise, and reached a steady state level of 31.5±0.80°C after 23 minutes of exercise. The course of $\bar{T}_{sk}$(K1), $\bar{T}_{sk}$(K4) and $\bar{T}_{sk}$(K5) were alike and they all reached values in between $\bar{T}_{sk}$(K2) and $\bar{T}_{sk}$(K3) (see Figure 1). At 30min both $\bar{T}_{sk}$(K2) and $\bar{T}_{sk}$(K3) had become significantly different from these three. Immediately after the cessation of EX1 $\bar{T}_{sk}$ increased 0.1 to 0.2°C with all clothing systems, but after 5 minutes of rest $\bar{T}_{sk}$ began to decrease again. Throughout RE1 $\bar{T}_{sk}$(K2) was higher than the $\bar{T}_{sk}$ with the other four knit constructions, except in the final minutes of RE1 where $\bar{T}_{sk}$(K2) (30.1±1.09°C) was only significantly higher than $\bar{T}_{sk}$(K3) (29.4±0.88°C). Due to the decrease of $\bar{T}_{sk}$ during RE1, all $\bar{T}_{sk}$'s were lower at the beginning of EX2 when compared to the start of EX1. In all clothing systems the decrease of $\bar{T}_{sk}$ continued over the first minutes of EX2, but after a varying length of time, $\bar{T}_{sk}$ began to increase with all clothing systems: with K2 after 10 minutes of exercise, with K1, K4 and K5 after approximately 15 minutes of exercise and with K3 after 20 minutes of exercise. After 10 minutes of EX2 (70min) $\bar{T}_{sk}$(K2) was still higher than $\bar{T}_{sk}$(K3). At 80min and during the rest of EX2, $\bar{T}_{sk}$(K2) was higher than $\bar{T}_{sk}$(K1), $\bar{T}_{sk}$(K4) and $\bar{T}_{sk}$(K5) which all were higher than $\bar{T}_{sk}$(K3). A comparison of $\bar{T}_{sk}$ during EX1/RE1 and during EX2/RE2 showed that at the end of EX2 $\bar{T}_{sk}$ was at average (n=40) 0.4°C lower than at the end of EX1, and except for K5 this was significant for each clothing system. The course of all $\bar{T}_{sk}$'s during RE2 were similar to during RE1, except that all temperatures were 0.3 to 0.4°C lower during the second period .

Local skin temperatures: The course of the various local temperatures during the test varied according to location on the body (Figure 1). They all decreased initially during EX1, but except for the temperature at the lower back and the forearm they either began to increase after a certain time or reached a steady state level. After cessation of exercise all local skin temperatures had an initial increase before they all decreased throughout the rest periods. At the beginning of EX2, thigh skin temperature was the only skin temperature that was not significantly lower than that at the start of EX1. During EX2 all skin

temperatures, except the forearm, increased much more than during EX1, but only skin temperatures on thigh, chest and forehead reached the same values as at the end of EX1.

Knit structure of the underwear significantly influenced the course of the skin temperatures on the trunk (chest, upper and lower back) and on the calf. Differences seemed to exist also in thigh skin temperature; however, these differences were never significant at the 0.05-level ($p<0.1$). On the calf $T_{calf}(K2)$ was always higher than $T_{calf}(K5)$, at most times higher than $T_{calf}(K3)$ and at some times higher than $T_{calf}(K4)$. On the trunk $T_{sk}(K3)$ was generally lower than the skin temperatures under the other knit structures. On the chest significant differences only occurred in the last part of the two exercise periods (29min & 39min: $T_{chest}(K2)>T_{chest}(K3)$) (79min, 89min & 99min: $T_{chest}(K2)> T_{chest}(K3)$; $T_{chest}(K5)>T_{chest}(K3)$). No differences in T_{chest} between knit structures were demonstrated during the rest periods. On the lower back $T_{lb}(K3)$ decreased more than T_{lb} under the other knit constructions and at 39min $T_{lb}(K3)$ was lower than $T_{lb}(K2)$ ($p<0.05$). Also, $T_{lb}(K3)$ tended to be lower than $T_{lb}(K4)$ and $T_{lb}(K5)$, but this was only significant occasionally. The skin temperature on the lower back decreased to quite low values even during work. In most subjects values between 25 and 27°C were recorded, and in the heaviest subject with 23% body fat an even lower skin temperature of 22°C was measured.

<u>Mean body temperature</u> was significantly influenced by knit structure from 29min and throughout the test (29-119min: K2> K3; 69-109min: K2> K1; 89-99min: k2> K4). Body temperature was at average 0.07-0.20°C lower in EX2/RE2 compared to EX1/RE1 ($n=40$; $p<0.05$); however, this was not significant for K2 at any time, and for K1 and K5 only at time 9 vs 69min.

<u>Onset of sweating</u>, was considered to take place when the dew point sensors at the skin recorded an increase in vapor pressure and it began at average 9±3.6 minutes (range 4-19 min) after the start of the exercise. An ANOVA did not confirm any difference in the time to onset of sweating between the five clothing systems; however, there was a tendency towards an earlier onset of sweating in K2 and K5 compared to K1, K3 and K4. There was no difference in the time to onset of sweating between EX1 and EX2. <u>Evaporation of sweat</u> registered on the Potter balance, began at average 12 min after the start of the exercise and

thus 3 minutes after the onset of sweating (Figure 2). No differences between knit types could be demonstrated and no differences between EX1 and EX2. Evaporation rate, E_{sk}, was at average 50, 40, 45 and 43 $W \cdot m^{-2}$ in the periods of EX1, RE1, EX2 and RE2 (that is, 2.4, 2.0, 2.2 and 2.1 $g \cdot min^{-1}$) (n=40). No significant differences could be attributed to the knit constructions, as the variation in E_{sk} was rather large. However, in EX1 E_{sk}(K3) and E_{sk}(K4) tended to be lower than E_{sk} with the other knit structures ($p<0.1$). The amount of sweat evaporated from the skin, Sw_e, was significantly influenced by knit construction and the differences between the clothing systems increased during the course of time (Figure 2). At the end of EX1 (40min) Sw_e(K3) was lower than Sw_e(K5), at the of RE1 (60min) and EX2 (100min) Sw_e(K3) was lower than Sw_e(K1), Sw_e(K2) and Sw_e(K5), and Sw_e(K4) was lower than Sw_e(K5). At the end of the test (120min) both Sw_e(K3) and Sw_e(K4) were lower than Sw_e(K1), Sw_e(K2) and Sw_e(K5) (Figure 3). The total amount of non-evaporated sweat, Sw_{ne}, sweat/humidity absorbed in the clothing ensemble worn during the experimental period, was also significantly influenced by the knit structure of the underwear (Figure 3). More sweat was found in the clothing system when K2 was worn compared to K1, K3 and K4. Of this non-evaporated sweat only 8, 22, 8, 10 and 11% were located in the underwear of the five clothing systems (K1 to K5). Total sweat production, Sw_{tot}, could only be determined at 120min, when Sw_{tot}(K3) and Sw_{tot}(K4) were lower compared to both Sw_{tot}(K2) and Sw_{tot}(K5) (Figure 3).

Skin wettedness: The knit structure of underwear significantly influenced the degree of skin wettedness during the course of the intermittent exercise (Figure 4). After onset of sweating, skin wettedness increased abruptly in both exercise periods to reach a steady state or near steady state level. Immediately upon the cessation of exercise, percent wettedness on the thigh increased, a tendency that was also seen on the chest, whereas on the upper back no such increase was observed. After 3 to 4 minutes of RE1 wettedness began to decrease and this decrease continued even after EX2 had begun. With the different knit structures average skin wettedness, w, reached values from 50 to 68% at the end of the exercise periods. w(K2) was always higher than w(K3). From 30min to the end of RE1 w(K2) was higher than w(K1), w(K3) and w(K5), and from 90min to the end of the test w(K2) was higher than the average skin wettedness with all the other knit

structures. Throughout the test w(K3) tended to be lower than wettedness under all the other knit structures, but being only significant at 30min. On the upper back skin wettedness was generally higher than at the chest and the thigh, reaching average values from 59% to 71% at the end of EX1 and 60% to 77% at the end of EX2. Influence of knit structure on upper back wettedness was significant at 60min and 70min (K2>K3), and at 110min and 120min (K2>K3; K2>K5). At the chest the influence of knit structure on skin wettedness was more pronounced. Except for the first minutes of the two exercise periods (10min and 70min) w(K2) was always higher than w(K3), w(K2) was mostly (20-40min & 90+120min) higher than w(K1), and at 40min and 90-110min higher than w(K4) and w(K5). At the thigh w(K2) was higher than w(K3) and w(K5) at 30-50min and at 100-110min. Generally, wettedness was slightly higher in EX2 and RE2 compared to EX1 and RE1.

DISCUSSION:

Knit structure of the underwear in a prototype two-layer clothing ensemble had no influence on core temperature, but had a significant influence on the thermoregulatory responses at the skin during intermittent exercise in a cold environment. Both the degree and the effectiveness of sweating during the periods of work-produced heat stress, and the cooling of the skin during the subsequent rest periods varied depending on the knit structure of the polypropylene underwear worn. Earlier studies on the physiological significance of underwear during intermittent exercise in the cold have focused on the importance of fiber type material (Vokac et al. 1976; Holmér 1985). Only small differences were observed. Thus, the knit structure of underwear is of far more importance regarding thermoregulatory responses than fiber type material, when working in the cold.

The underwear constructions selected for this study varied in thickness (3 levels) and in porosity (3 levels), and these differences were reflected in the measured thermal characteristics of the underwear textiles (Table 1). When doing a comparison of the thermal characteristics of the five clothing systems under stationary conditions as described for standard measurements on two-layer textile samples and on a thermal manikin, the differences in thermal resistance and moisture vapor transport were small. This was expected for the measurements on the non-moving manikin, where the tight-fitting

underwear adds little extra insulation to the clothing ensemble. The insulation of the clothing ensemble is primarily determined by the amount of enclosed non-moving air, and thus by the design and fit of the outermost garment (McCullough et al., 1985). Some of the differences found in the standard measurements of the textiles were reflected in the thermoregulatory responses. The heavy fleece structure (K2) was the thickest textile, had the highest thermal and water vapor resistance, and it also resulted in the warmest thermoregulatory responses with highest skin temperatures, highest skin wettedness, most total sweat produced, and most unevaporated sweat. However, the K1-system with the thin 1-by-1 rib-knit underwear, which had the lowest thermal resistance and a comparably low water vapor resistance, did not result in the coldest thermoregulatory responses in the human tests. This was found in the K3-system with the open fishnet underwear, where we observed the lowest skin temperatures, the lowest skin wettedness and a low total sweat production that also resulted in a smaller amount of evaporated sweat. This comparably colder response could not have been expected based on the textile and manikin data, where the K3-system ranked second with regard to thickness and thermal resistance, although lowest in water vapor resistance.

The differences between the results from static measurements on samples of textiles and of garments on a manikin, respectively, and responses in human tests must be explained from the dynamic condition within the microclimate of the clothing systems during the exercise in the actual test environment. An external air velocity of 0.32 $m \cdot s^{-1}$ will remove part of the insulating boundary air layer adjacent to the clothing system lower the resistance to both diffusion of heat and water vapor (Burton and Edholm, 1955). The external air may also penetrate into the clothing producing convection within the entrapped air, reach the underwear and then, eventually, the air directly at the skin surface. These convective air movements will add to those created within the microclimate by bodily movements, resulting in the bellows or pumping effect (Vokac et al., 1973). An open structure such as the fishnet construction will allow for the moving air to sweep directly over the skin, whereas a heavy and tight construction such as the fleece will only allow a limited degree of air to reach the skin surface. Therefore, a steeper gradient from skin surface to microclimate results with regard to temperature and water vapor

pressure in K3 compared with the other constructions, especially K2. Skin temperature and skin wettedness reflects this, reaching lower values under an open knit structure. Even without the external air velocity, the pumping of air within the clothing ensemble would probably have resulted in differences in the thermoregulatory responses at the skin in this study. In a clothing ensemble with more layers than applied here, the external air may not reach the skin under a tight fitting underwear, depending on closures and the air permeability of the outer layers.

Air movements within the clothing microclimate can explain the differences found in skin temperature, but not the differences observed in the sweat data. With skin temperature as one determinant of sweat production, the observed high sweat production with K2 and the low with K3 may result from different skin temperatures. However, with K1, K4 and K5, mean skin temperatures were not different, but sweat production tended to start earlier and was significantly higher with K5 than K4. The minor differences in the textile characteristics do not provide an explanation for this. Of the total sweat produced, 74% was evaporated, 26% unevaporated and the ratio non-evaporated/evaporated was 36% in both K4 and K5; but the total sweat production was significantly larger with K5 than K4. It was interesting to note in all clothing systems that it took approximately 3 minutes from start of sweat production until sweat began to evaporate to the environment.

Regional differences in the thermoregulatory responses were quite large. Generally the back seemed warmer than the front. Differences between chest and upper back in regard to skin temperature and wettedness were small with the fleece underwear (K2); however, with the other knit structures, and especially with the open fishnet underwear (K3) differences became more. This supports the theory proposed above, that air blowing towards the front of the subject increases the convective heat exchange and removes humidity-laden air, thus ameliorating the conditions for diffusion of vapor and heat energy. The back is the lee side and therefore is less influenced by the air velocity. This would also be expected to occur at the lower back; however, here unusually low temperatures were recorded. Whether this implies an effective ventilation of the clothing microclimate in this area, a thicker subcutaneous fat layer than at the other measuring places on the trunk, or sweat running down the back or moving down in

the clothing at the back to stop at the lower back so a more effective evaporative cooling can take place at the skin, is unknown, and should be further studied. The largest effect of convective cooling and the pumping effect was observed on the legs, where cessation of exercise caused an immediate increase in both skin temperature and wettedness before both slowly began to decrease again. Although the BDU-trousers were closed at the ankles, there was a large variation in skin temperature on the calf dependent on knit structure of the underwear.

It was decided to use an intermittent exercise test rather than one continuous exercise period followed by a period of rest as applied by Holmér (Holmér, 1985). It was hypothesized that a dampening or wetting of the clothing system would occur over the course of EX1/RE1 and that this might change the course of the thermoregulatory responses in the second period. A lower mean skin temperature and a higher skin wettedness was actually observed. The hydrophobic polypropylene fiber material in the underwear hindered extensive sweat accumulation in the underwear (max average was 25g in K2). Instead, accumulation of sweat took place in the outer garment layer, especially the jacket. Therefore, we did not have a sweat soaked textile in contact with the skin that increased the conductive heat loss, and, the lower skin temperature recorded in the second period must be explained by a lowering of the total insulation of the clothing system caused by the dampening or wetting of the ensemble. It has earlier been shown that wetting of clothing lowers its insulation (Hall and Poltke 1956; Pugh 1966). With the method used in the present study it was not possible to decide at what time the absorption of sweat took place. However, the first minutes after cessation of exercise when sweat production is still high but ventilation is considerably decreased, was probably the period of the most sweat absorption.

For work in a cold environment it is usually recommended not to dress too warmly. The rationale is, that with a warmer dress, more sweat will be produced, more sweat then be absorbed in the clothing resulting in a greater decrease in clothing insulation, and finally a greater cooling of the body in subsequent rest periods. The data obtained in the present study does not support this idea. After 20 minutes of rest mean skin temperature was still higher with the warm underwear (K2) compared to the fishnet underwear (K3). There is no reason to believe that a longer rest period would change this. However,

with a more hydrophilic fiber type material such as cotton, this may not be the case.

In summary, knit construction of underwear in a clothing ensemble had no influence on core temperature, but had a significantly large influence on the thermoregulatory responses at the skin during intermittent exercise in a cold environment. Both the degree and the effectiveness of sweating during the periods of work-produced heat strain, and the chilling of the skin during the consecutive rest periods varied dependent on the knit structure of the polypropylene underwear worn.

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Table 1.

Knit Structure	1-by-1 rib K1	Fleece K2	Fishnet K3	Interlock K4	2-layer K5	BDU
TEXTILE SAMPLES						
Fabric thickness (mm)	.84	1.65	1.04	1.04	.81	.58
+ BDU on top	1.33	2.06	1.40	1.43	1.30	
Thermal resistance*	.156	.193	.139	.148	.147	.121
+ with BDU on top ($m^2 \cdot K \cdot W^{-1}$)	.165	.208	.166	.160	.164	
Water vapor resistance**	15.0	19.5	17.1	15.4	16.0	12.5
+ with BDU on top ($m^2 \cdot Pa \cdot W^{-1}$)	21.7	23.8	20.2	23.8	23.4	
THERMAL MANIKIN						
Total thermal resistance (R_{tot}) *** ($m^2 \cdot K \cdot W^{-1}$)						
Underwear ensemble only	.136	.164	.140	.144	.144	
Clothing system	.243	.268	.256	.248	.250	

* Includes thermal resistance of air: .106 $m^2 \cdot K \cdot W^{-1}$
** Includes water vapor resistance of air: 8.8 $m^2 \cdot Pa \cdot W^{-1}$
*** Includes thermal resistance of air (R_a): .104 $m^2 \cdot K \cdot W^{-1}$

LEGENDS

Table 1. Physical characteristics of the textiles applied and of the garments measured on a thermal manikin.

Figure 1. Esophageal, mean skin temperature and local skin temperatures during the course of the intermittent exercise (n=8). Symbols: K1 •, K2 ■, K3 >, K4 o, K5 *.

Figure 2. Average evaporative weight loss during the course of the intermittent exercise (n=8). Symbols: K1 •, K2 ■, K3 >, K4 o, K5 *.

Figure 3. Total sweat production, evaporated and non-evaporated sweat (mean±sd).

Figure 4. Skin wettedness at average, and locally on upper back, chest and thigh during the course of the intermittent exercise (n=8). Symbols: K1 •, K2 ■, K3 >, K4 o, K5 *.

Figure 1.

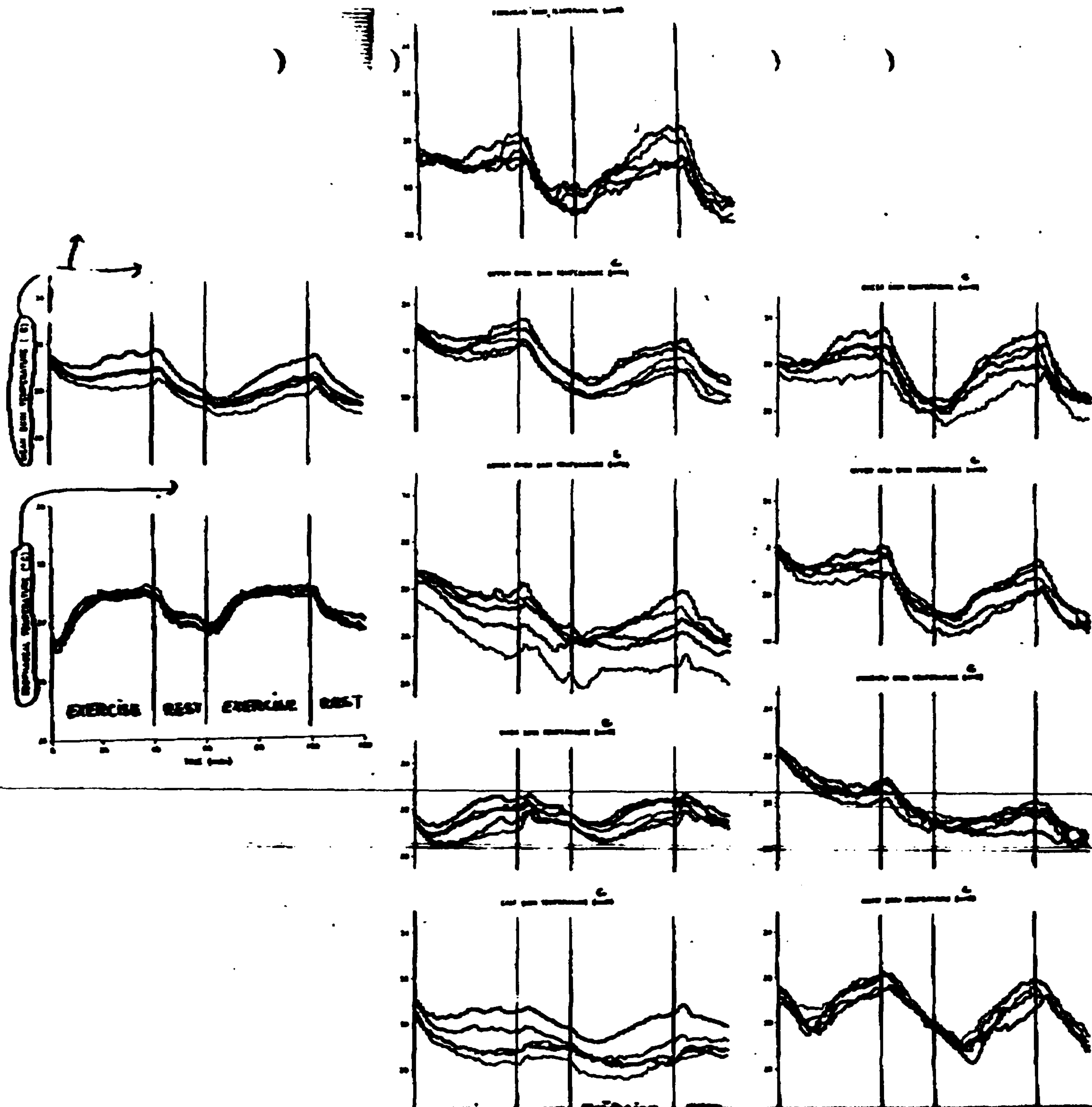


Figure 2.

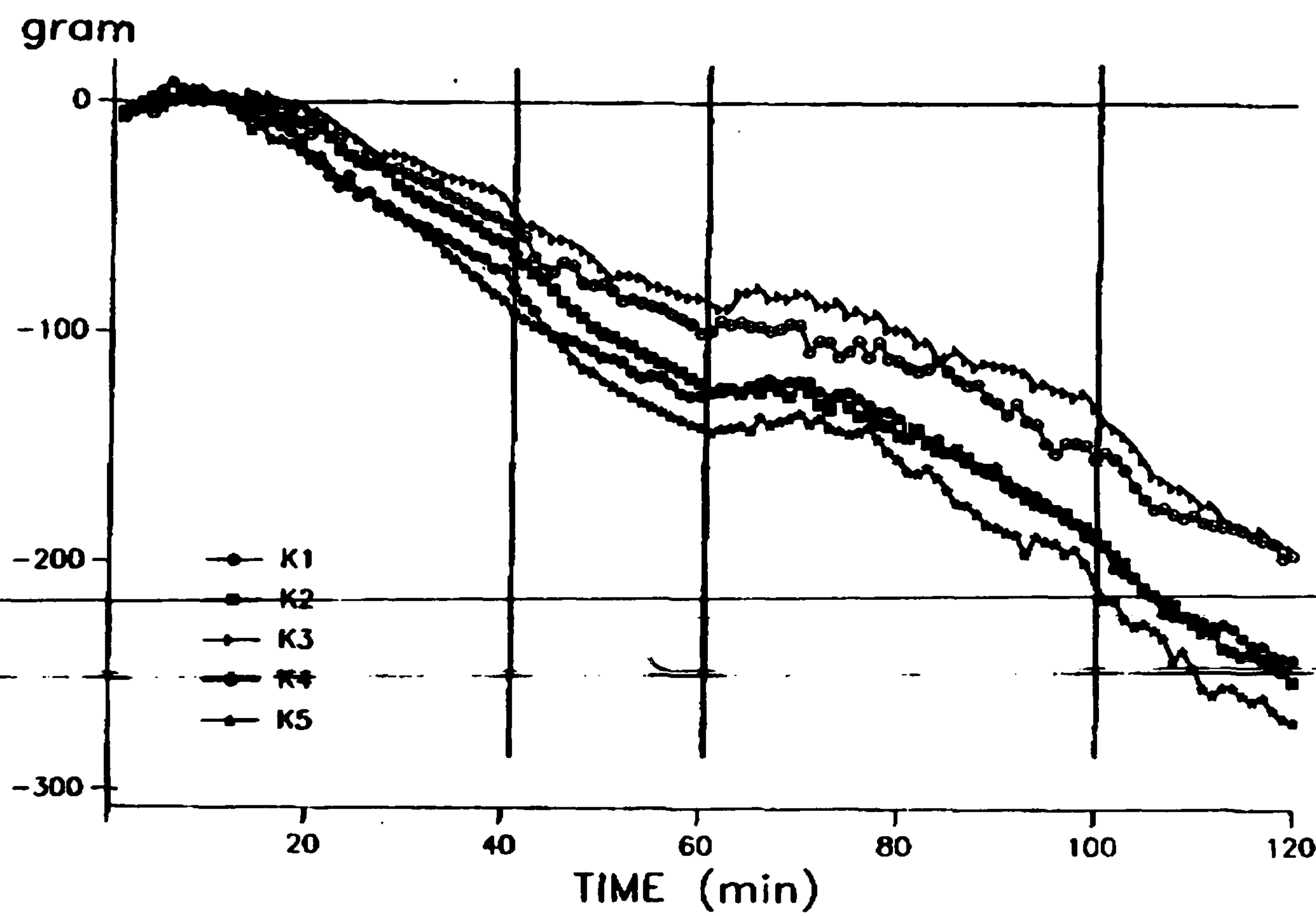
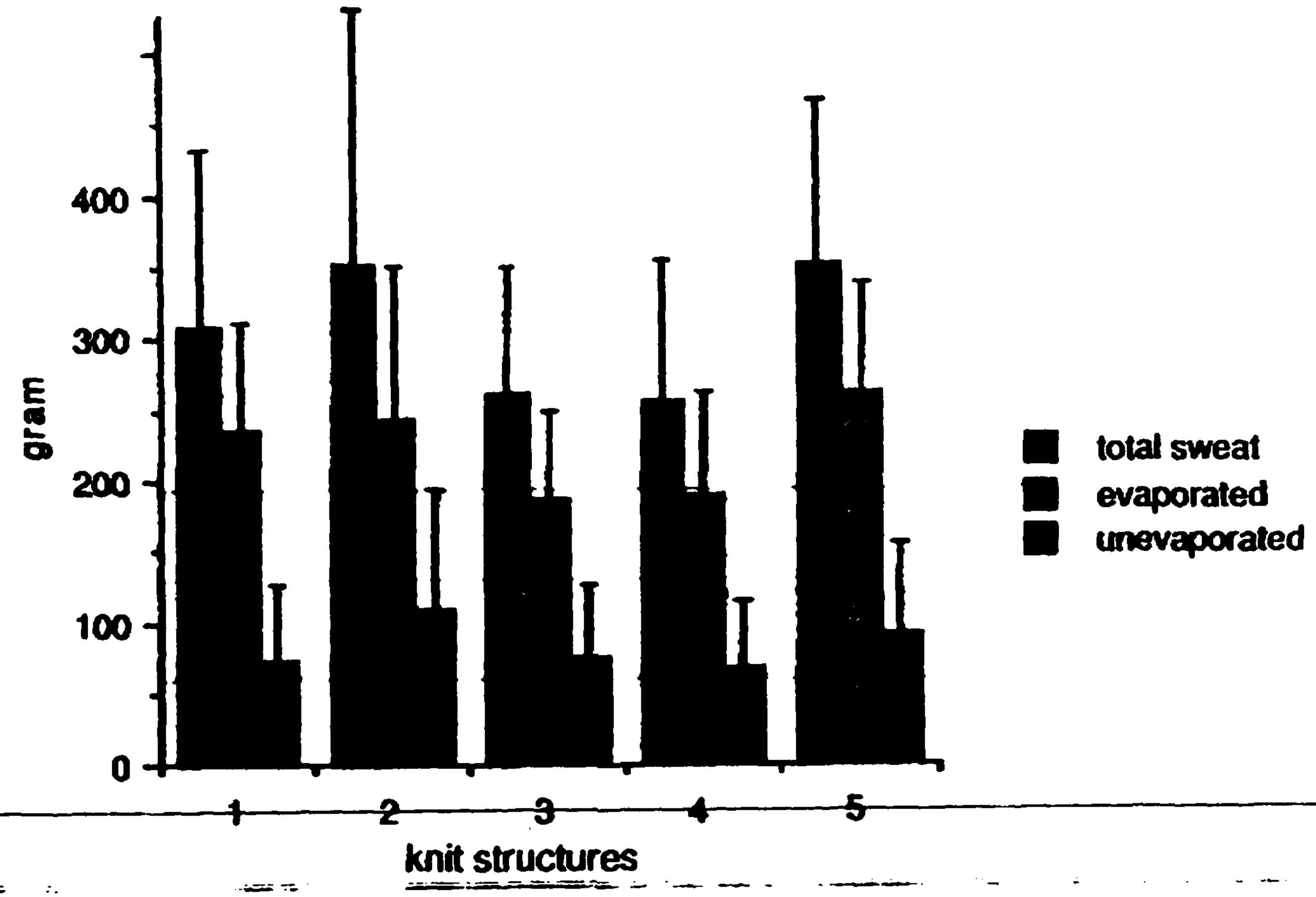
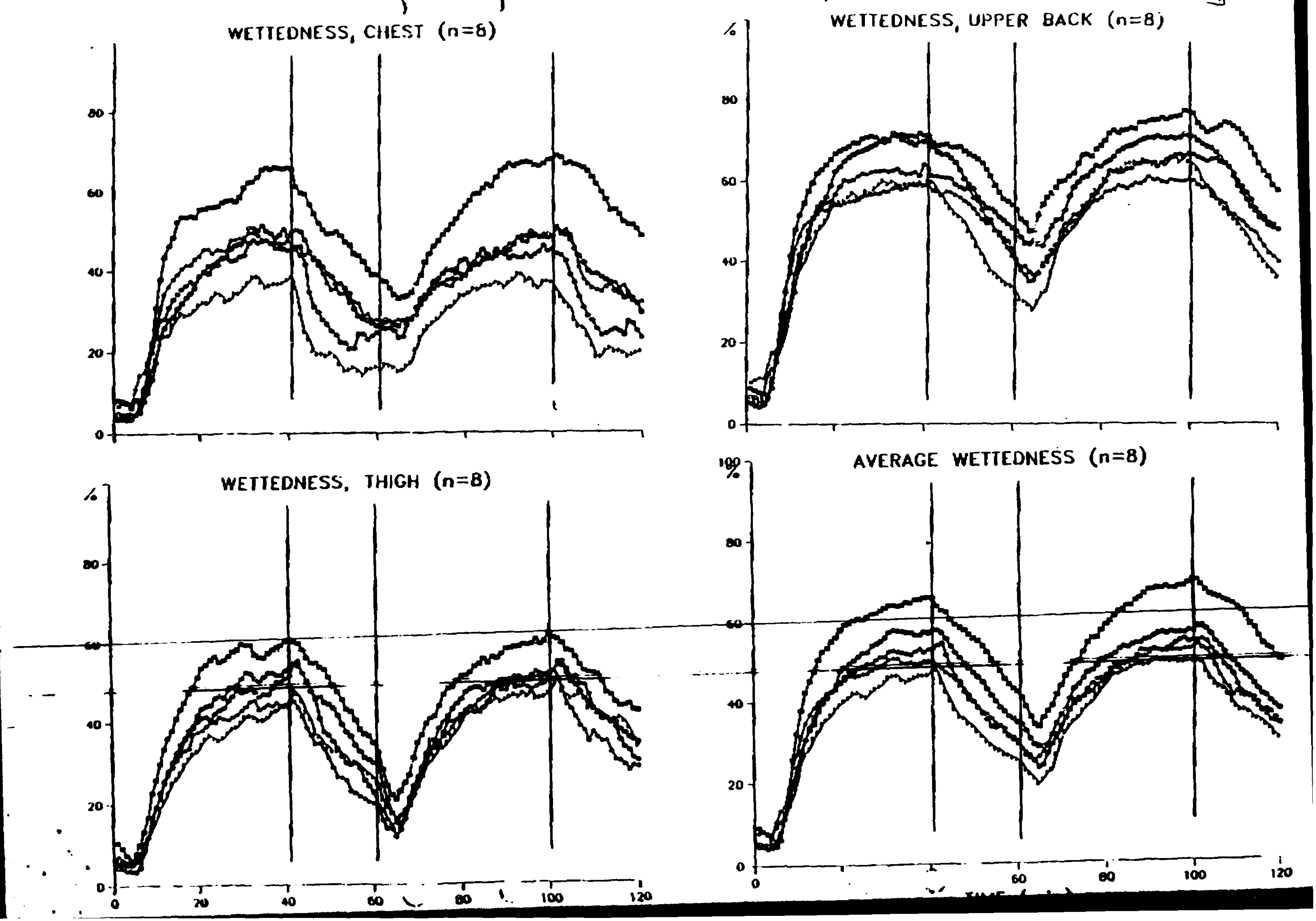


Figure 3.



400
300
200
100
0
gram
1
2
3
4
5
knit structures
total sweat
evaporated
unevaporated

Figure 4



WETTEDNESS, CHEST (n=8)
WETTEDNESS, UPPER BACK (n=8)
WETTEDNESS, THIGH (n=8)
AVERAGE WETTEDNESS (n=8)
%
0
20
40
60
80
100
120